

Interpretation of Light-Quenching Factor Measurements

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We observe that the pattern of the quenching factors for scintillation light from various ions, recently studied in CaWO_4 in connection with dark matter detectors, can be understood as a saturation phenomenon in which the light output is simply proportional to track length, independent of the ion and its energy. This observation is in accord with the high dE/dx limit of Birks' law. It suggests a simple model for the intrinsic resolution of light detectors for low energy ions, which we briefly discuss.

INTRODUCTION

Comparison of light and heat signals is proving to be an effective method of background reduction in cryogenic dark matter searches [1]. In addition, a detailed understanding of the reduction of the light signal for different recoiling nuclei may be quite significant for such searches. In a detector material containing a variety of nuclei, it could permit the identification of which type of nucleus has been struck. This would allow study of a possible dark matter signal for different target nuclei in one and the same experimental setup. Since a simple behavior in the shape of the recoil energy spectrum is expected with respect to the mass of the target nucleus, this would be a great experimental simplification and an important check in verifying the dark matter signal [2]. Furthermore, comparison of the rates on different nuclei would be useful in learning about the properties of the dark matter particle [3].

QUENCHING FACTOR CURVES

For these reasons the CRESST collaboration has undertaken a series of studies by various methods of the scintillation light produced in CaWO_4 , the material presently used in CRESST. The results are presented in terms of the quenching factor, the reduction factor for the light output for a given ion compared to that of an electron of the same energy.

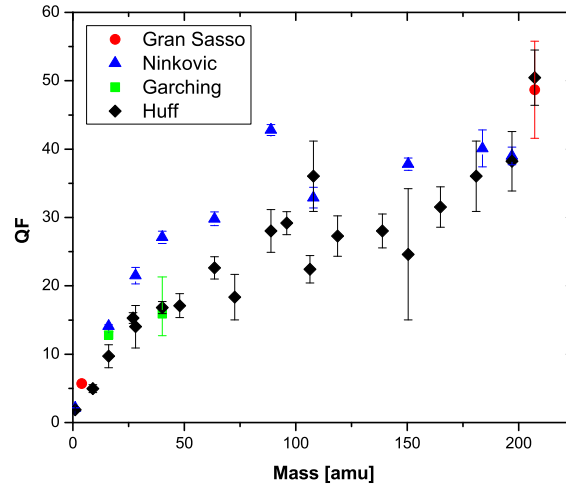


FIG. 1: Measurements of the quenching factor in CaWO_4 .

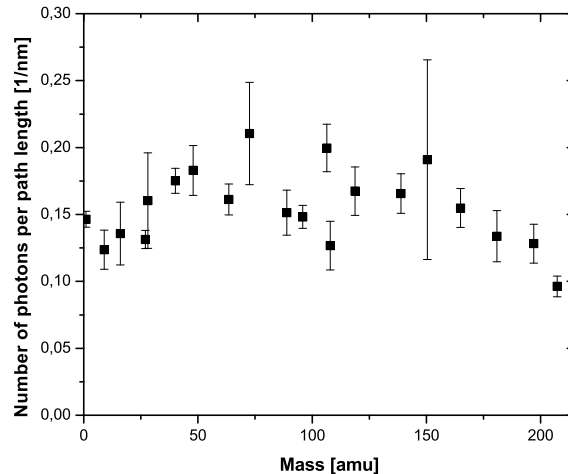


FIG. 2: Photons per unit L for various ions, using the data of ref[5] at 18 keV and “path lengths” L calculated from the SRIM programs as explained in the text. “Number of photons” on the vertical axis simply refers to detected photons, no attempt has been made to account for efficiencies. Error bars are from the experimental data, fluctuations in the calculation of L are on the order of a few percent.

The quenching factor is a convenient quantity experimentally since a calibration may be performed by placing a gamma-ray source, which produces photoelectrons, in the same apparatus as one is using to study the ions. This obviates the need to understand the absolute efficiencies for light collection and detection since these will presumably be the same for electron- and ion- induced scintillation light. On the other hand, the interpretation then involves the light output for electrons as well as that for ions.

The measurements have been performed at room temperature with ions projected onto a $CaWO_4$ crystal [4], [5], and with nuclear recoils induced by neutron scattering [6]. In addition a low temperature determination was possible using data of a prototype run in 2004 (Run 28) of the CRESST light/heat detectors in the Gran Sasso laboratory, through the identification of a group of events as ^{210}Po decays [7].

Fig 1 shows these various results. One observes a rough consistency among the different methods. There are two main points to be noted: A) a smooth systematic increase in the quenching factor with the mass or Z of the ion, and B) an approximate energy independence of the quenching factor, since the various methods involve ions of different energies, ranging from 18 keV to 2.2 MeV. The low temperature (Gran Sasso) results also suggest there is not a strong temperature dependence[8].

PROPORTIONALITY OF LIGHT TO “TRACK LENGTH”

In this note we would like to point out a simple interpretation of these data. We start with the question of the dependence on the type of ion, that is for data at fixed energy. The quenching factor is the reduction factor with which one divides the light output for an electron to find the light output for an ion of the same energy. Thus at fixed energy the light output for an ion is proportional to the inverse of the quenching factor.

$$light_{ion} = \frac{1}{quenching\ factor} light_{electron} \quad (1)$$

Among the quantities associated with passage of an ion in a material there are the ranges or the track lengths. These quantities may be found by simulations of the slowing down process, as from the SRIM [9] and STAR [10] programs. We shall work with a quantity we call L which we obtain from the SRIM results as follows:

$$L = \sqrt{R_{long}^2 + R_{rad}^2}, \quad (2)$$

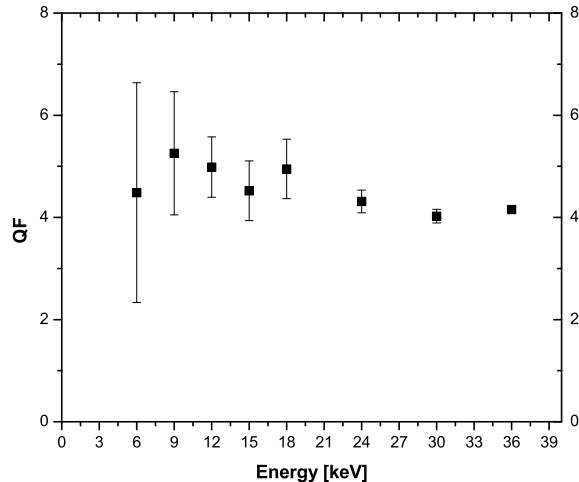


FIG. 3: Energy dependence of the quenching factor for Be, from ref[5].

where the R 's are the average longitudinal and radial ranges provided by the simulation. L is intended to provide a representation of the effective length of the track (see the remarks in “Discussion”). Now, plotting $1/L$, one finds a striking resemblance to the pattern of points in Fig 1. In view of Eq 1, this suggests that the light output for an ion may be simply proportional to its “track length”.

To make this point most effectively we show in Fig 2 the light yield divided by L for different ions, using the 18 keV data of ref[5]. One observes that the points scatter around a common value, in agreement with the idea that the light output is simply constant per unit “length of track”. In this picture of a constant light production per unit length, one would assume that there is a saturation value of dE/dx where this constant value of light output dl/dx is attained, characteristic of the material (here $CaWO_4$) but independent of the projectile and its energy.

ENERGY DEPENDENCE

As remarked above, a second interesting feature of the data is the approximate energy independence of the quenching factor. The data of Fig 1 represents a relatively wide span of energy, ranging from 100 keV for the ^{210}Po decays or MeV's for the neutron-induced recoils, down to 18 keV for the accelerated ions. The fact that these various results are generally in agreement indicates that the quenching factor is roughly energy independent in this range. A direct measurement was also possible with Be ions using multiply charged states in the ion accelerator of ref[5], as shown in Fig 3. The range of energies is that relevant for CRESST and most dark matter searches in general.

If dE/dx is above the saturation value for all energies encountered during the slowing down process, we naturally obtain that the light production is proportional to the track length for any projectile, and furthermore that it is dependent on the initial energy only through the track length. The track lengths in $CaWO_4$ at these energies appear in fact to grow approximately linearly with energy, as shown in Fig 4, so that the light output for ions should also increase approximately linearly with energy.

To finally obtain an energy independent quenching factor we require that the light output for an electron also be linear with the energy. That this is indeed true is shown by fact that the electron/photon band in the light/energy plane, as reproduced in Fig 5 from ref[1], is approximately straight. If the band is straight, the light yield is proportional to the total energy. Also, direct tests with different gamma-ray sources have shown the linearity of the scintillation response [4], [5], up to 1.3 MeV.

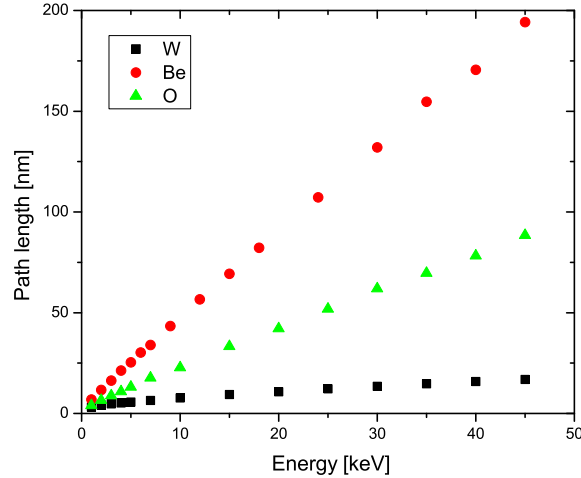


FIG. 4: “Track lengths” L in $CaWO_4$ calculated from the SRIM simulation program.

LIGHT OUTPUT FROM ELECTRONS

It is interesting to inquire where the point for electrons would lie on Fig 2, that is, how the light production per unit L for electrons compares to that for ions. Since electrons are much less ionizing than ions we of course expect the value to be smaller. We may estimate the ion/electron ratio by taking a typical ion, say oxygen, and using

$$\frac{(\text{light per unit } L)_{\text{oxygen}}}{(\text{light per unit } L)_{\text{electron}}} = \frac{\text{light}_{\text{oxygen}}}{\text{light}_{\text{electron}}} \frac{L_{\text{electron}}}{L_{\text{oxygen}}} = \frac{1}{\text{quenching factor}} \frac{L_{\text{electron}}}{L_{\text{oxygen}}}. \quad (3)$$

The quenching factor for oxygen is about 8. At 20 keV L_{electron} in $CaWO_4$ is about $1.7 \times 10^3 \text{ nm}$ [10], to be compared with the 40 nm for oxygen in Fig 4. Thus

$$\frac{(\text{light per unit } L)_{\text{oxygen}}}{(\text{light per unit } L)_{\text{electron}}} \approx \frac{1}{8} \frac{1700}{40} \approx 5. \quad (4)$$

That is to say, a saturated track in $CaWO_4$ produces about five times as much light per unit “length” as a 20 keV electron does, when averaged over its whole path; and so the electron point on Fig 2 would lie a factor five below the others. It appears that while the number of photons per unit length of track for electrons is of course less than that for ions, it is not orders of magnitude smaller at these energies.

It is interesting to remark, finally, that the approximate proportionality of light output to energy apparently arises for electrons and ions for different reasons. For ions, as explained above, the saturation of the light output l per unit track length L , together with the approximate linear growth of L with energy, gives the proportionality. For electrons on the other hand we have low dE/dx , where Birks’ law [11] reads $dl \sim dE$. Upon integrating, this gives $l \sim E$, whether the range is growing linearly with energy or not.

DISCUSSION

We have placed the words “track length” in quotation marks throughout because the exact interpretation of the quantity L , Eq 2, is not clear. At these energies it is not evident that there is something like a roughly well-defined track for the ion. A low energy ion in a dense material has a very irregular path and will create many recoils along the path. In Fig 6 we show two examples of tracks, with recoils, from the SRIM program. In the left panel one sees that despite the recoils a more or less well-defined track exists. In the right panel, however the projectile ion has changed direction radically and the notion of a definite track appears more doubtful. Furthermore, the “track length” of Eq 2 does not account for most “wiggles” along the track, and in addition the square root of the sum of squares of averages

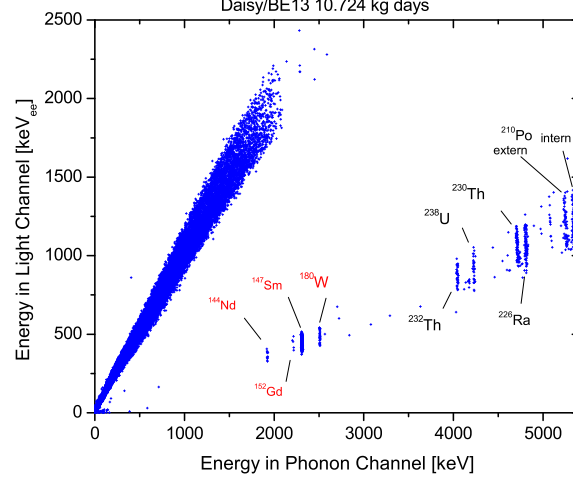


FIG. 5: Events in the energy (phonon)-light plane, showing alpha particle and electron-photon bands. From ref [1], Fig 7.

is not the same as average of a quantity itself. The neglect of “wiggles” can have a great effect on estimates of the total track length, as the often substantial “detour factor” supplied by the STAR calculations shows.

But on the other hand it is not evident that the track length of just the incident ion is the relevant quantity. A significant portion of the initial energy goes into the recoils and the saturation region around the track must have some definite width, so many of the “wiggles” will be ineffective in light production. It seems most appropriate to consider L as a measure for the linear dimension of the excited region of the scintillator; this appear to be an approximate but nevertheless useful quantity, as our results show.

These subtleties should become unimportant at higher energy, where we can comfortably identify L with the ordinary track length. The energy where this occurs can be gauged from plots of the “detour factor”, which typically approaches one around a few MeV [10].

Turning now to the saturation of the light output, this is incorporated in Birks’ Law for scintillation light output per unit length, $dl/dx \sim \frac{dE/dx}{1+kBdE/dx}$, in the high dE/dx limit. For inorganic scintillators it is discussed in Birks [11], chapt. 11 and in Rodnyi [12], section 2.3.5. As discussed in these references the extensively studied NaI-Tl or CsI-Tl scintillators show the transition to the saturation regime taking place for dE/dx between some tens of MeV/gm cm^2 and about 100 MeV/gm cm^2 .

We can try to estimate the saturation dE/dx in our $CaWO_4$ data from the fact that at 18 keV saturation appears to have occurred for protons (first point on Fig 2) but has not for electrons. At 18 keV for electrons dE/dx in $CaWO_4$ is about 8 MeV/gm cm^2 [10], while for protons it is 160 MeV/gm cm^2 [9]. We may conclude that for $CaWO_4$ then

$$8 \text{ MeV/gm } cm^2 < \left(\frac{dE}{dx} \right)_{saturation} < 160 \text{ MeV/gm } cm^2. \quad (5)$$

This span is rather broad, but of course the saturation turns on gradually, and the values are in the general range just mentioned. It is interesting to note that at these low energies the dE/dx for electrons is strongly increasing with decreasing energy, rising to 37 MeV/gm cm^2 at 1 keV. Thus it is possible that towards the end of its range the light production along the electron track also begins to saturate.

COMMENT ON RESOLUTION OF LIGHT DETECTORS

In any detector system, there will be a limit to the resolution attainable because there are fluctuations in the underlying physical process. In the present case this is the production of scintillation light.

The picture suggested by our observation that the light output for ions seems just proportional to “track length” provides a simple model for these intrinsic fluctuations: the variations in “track length”, called straggling. On this model the ratio (straggling)/ (“track length”) would give the intrinsic fluctuation for the light production by ions.

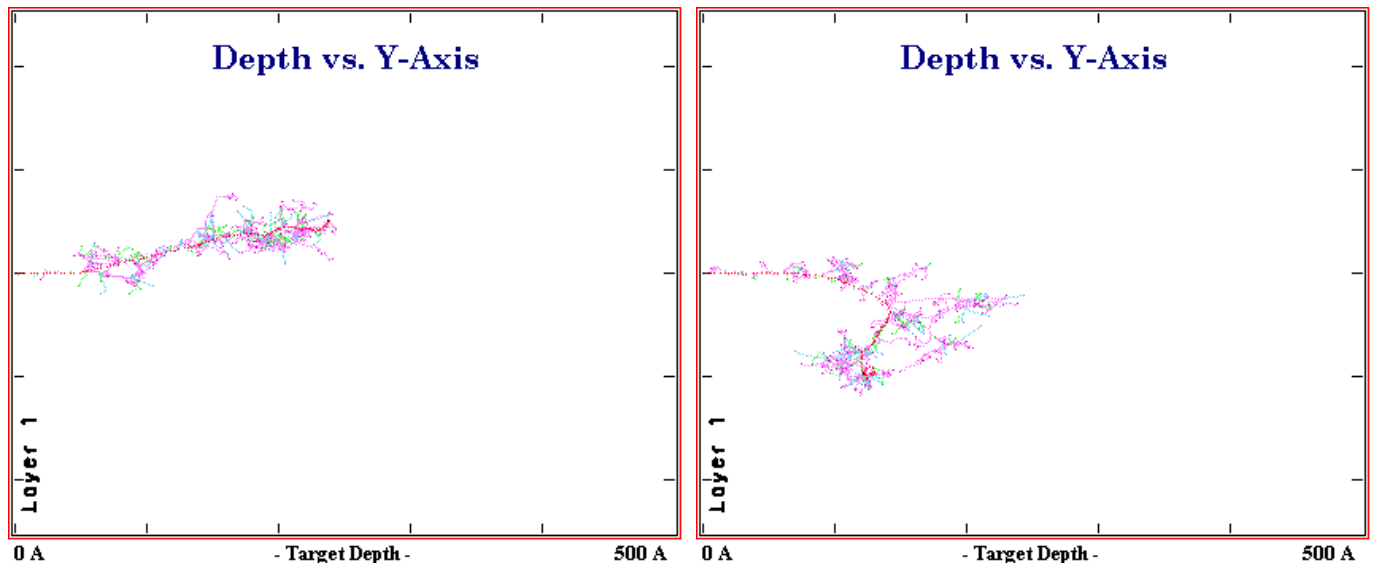


FIG. 6: Two examples of tracks of incident ions plus recoil nuclei produced in CaWO_4 by the SRIM simulation. An incoming 20 keV Ca ion is shown in red, with Ca (green), O(violet) and W (blue) recoils.

The SRIM program provides the fluctuations or straggling for the longitudinal and radial ranges. For a given ion and energy we add these in quadrature, as we did for the range itself in Eq 2, and call the result the “straggle” [13]. In Fig 7 we show the ratio (straggle)/L obtained from the program with Oxygen ions in CaWO_4 . The low energy value for this relative fluctuation seems quite large. However this is not in disagreement with the data of Meunier et al, [14] where CaWO_4 was irradiated with an Am-Be source, giving neutron-induced recoils. The spread of the nuclear recoil band obtained there also shows such large fluctuations at low energy. But evidently other sources of scatter in the data, such as the baseline (electronic) noise of the thermometer are present, and it is difficult to say if intrinsic fluctuations are being observed. (The nuclear recoil band is presumably dominated by Oxygen recoils; but simulations for Ca ions would give similar results.)

At higher energies the (straggle)/L ratio found from the simulations decreases. This is a consequence of the fact that while the range continues to increase more or less linearly with energy, the straggling turns over with increasing energy, growing more slowly than linear, and begins to resemble the \sqrt{E} behavior expected from an accumulation of small random fluctuations. In the MeV range (straggle)/L goes down to only some percent.

For alpha particles at 3 MeV the ratio from the simulation is 0.07. This is in marked contrast to the large width of the alpha band of Fig 5, which furthermore shows no tendency towards a $1/\sqrt{E}$ behavior. Presumably the fluctuations are dominated by other effects such as inhomogeneities in the crystal, giving position-dependent light production and escape. Such a hypothesis is supported by the fact that at the same average measured light output the electron and alpha bands in Fig 5 have closely the same spread. Furthermore we find that different crystals have different spreads [15] in the light output, while fluctuations of intrinsic origin should be the same for all crystals of the same material.

At the present time it thus does not seem possible to draw any firm conclusions as to the validity of a straggling model for the intrinsic resolution. It would be interesting to examine it with tests using different materials and energies. These considerations are of course only relevant when instrumental fluctuations are so well under control that intrinsic fluctuations become the limiting factor. However they do suggest that at low energy there may be a significant intrinsic limit to the attainable resolution.

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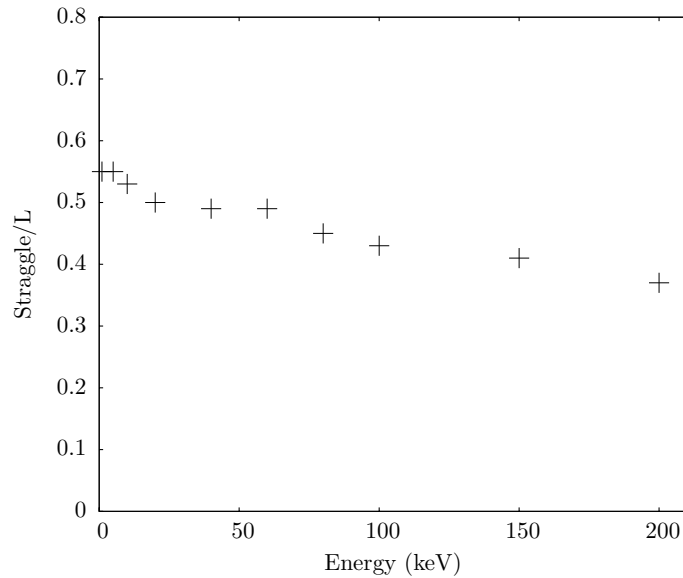


FIG. 7: Simulations for the ratio (straggle)/L from the SRIM program (see text), for Oxygen ions in $CaWO_4$.

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 - [6] Th. Jagemann et al., *Astroparticle Phys.* **26**, 269 (2006). (Points indicated as “Garching” on Fig 1.)
 - [7] See the discussion at the end of the section “quenching factors” in ref [1].
 - [8] Although it should be noted that V.B. Mikhailik, H. Kraus, S. Henry and A. J. B. Tolhurst, *Phys. Rev. B* **75** (2007), find a factor four jump in the *absolute* light output for $CaWO_4$ in going to low temperature.
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 - [10] The STAR programs are available at [/physics.nist.gov/PhysRefData/Star/Text](http://physics.nist.gov/PhysRefData/Star/Text).
 - [11] J. B. Birks, *The Theory and Practice of Scintillation Counting*, Pergamon Press, (1964). See Eq. 6.4, pg 187 and pg 439.
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 - [13] In SRIM “straggle” is the square root of the average square fluctuation. Thus in a Gaussian fit $\sim \exp[-\frac{1}{2}(\frac{l-l}{\sigma})^2]$ to the event distribution as a function of l the light output, “straggle” would be equivalent to σ .
 - [14] P. Meunier et al., *Appl. Phys. Lett.* **79** 1335 (1999).
 - [15] See table 1 of ref [1].